

# Determination of Earthquake Parameters

## Introduction

Improved seismic data and computer facilities have made dramatic progress possible in the computational techniques of earthquake location and the quantification of earthquakes. Some of the more proven techniques may well be ready for application in the routine reporting of earthquake parameters. Earthquake parameters serve as an important data base for the generalists and synthesizers in seismology and as an initial starting point for the applied theoreticians. The routine determination and reporting of source properties, for example, could make possible a new level of understanding in many seismological studies that would parallel the use of routinely reported earthquake locations to define boundaries of tectonic plates worldwide. These advances are made possible now through the availability of digitally recorded seismic data and of computer programs for interactive analysis that permit more rapid and efficient estimation of earthquake parameters.

To explore these new possibilities a special conference on the Determination of Earthquake Parameters, cosponsored by the U.S. Geological Survey and IASPEI (International Association of Seismology and Physics of the Earth's Interior), was held in the University of Denver's Lawrence C. Phipps Memorial Conference Center, Denver, Colorado, from March 19-21, 1979. Experts invited from universities and government agencies in the United States and abroad presented diverse opinions in oral presentations and open discussions. This report will attempt to synthesize the views expressed at that meeting and in later written comment by participants.

## Earth Structure

The effects of lateral variations in earth structure on seismic waves propagating in the earth may, if uncorrected or unidentified, lead to biased earthquake locations, misinterpretation of crust and upper mantle structure, and obfuscation of the deterministic part of a seismogram.

Teleseismic *P* wave delays can be a useful tool for resolution of crust and upper mantle structure beneath seismic networks. Recent studies in areas like the Rio Grande Rift reveal lateral variations in velocity that extend deep into the upper mantle.

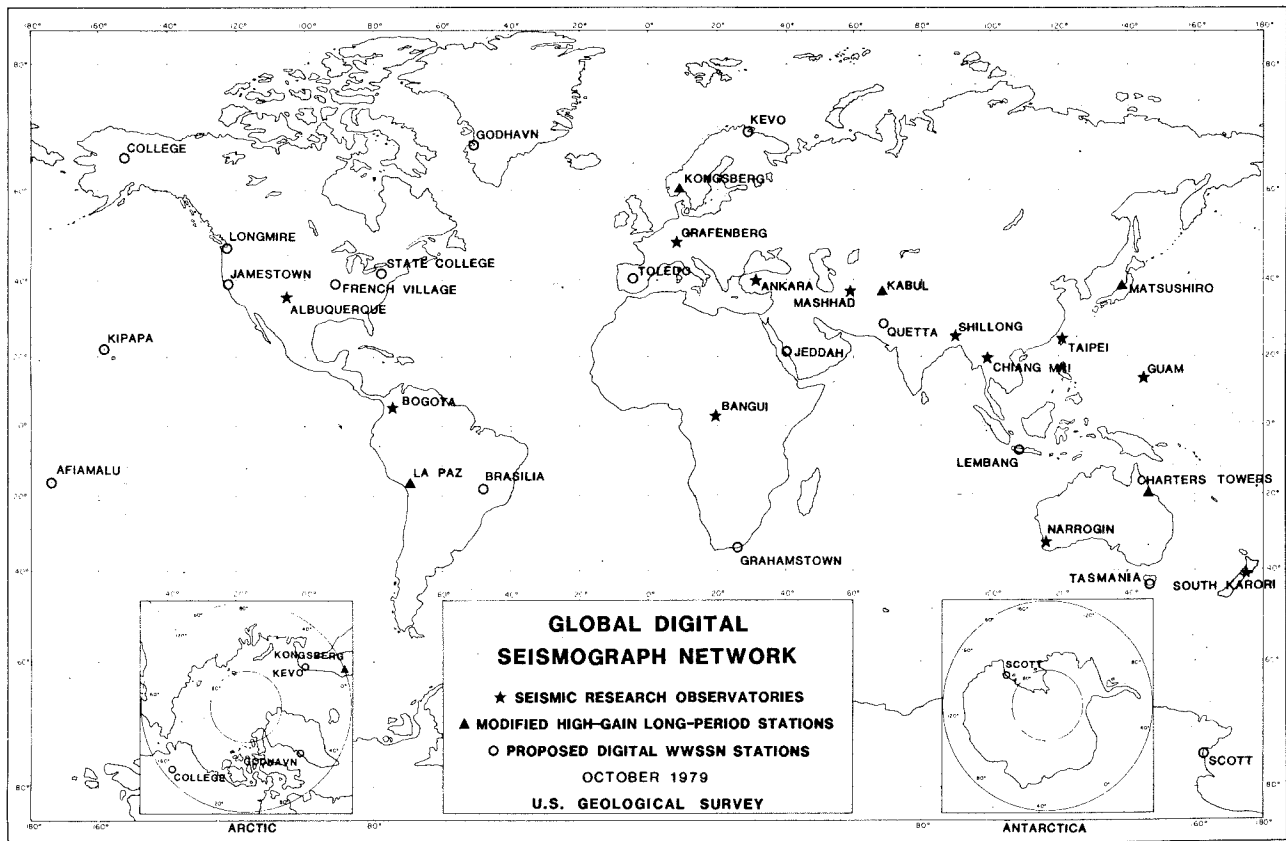


Fig. 1. The Global Digital Seismograph Network (GDSN). The Seismic Research Observatories (SRO) and modified High-Gain Long-Period (ASRO) stations shown on the map are operational. An additional SRO station will be installed in the future. The sites shown for the digital WWSSN (DWWSSN) stations are based, for the most part, on siting recommendations made by an ad hoc panel of scientists convened by the NAS/NRC Committee on Seismology. The site locations are tentative, as cooperative arrangements have not been concluded at this time. The Jamestown and Jeddah stations will not have WWSSN instruments, but data bands and format will be identical to the digital WWSSN. (Figure prepared by Albuquerque Seismological Laboratory.)

Statistical analysis of individual station travel time residuals routinely reported in catalogs reveals systematic differences from the global average that can be attributed to certain structural features in the earth. It has already been demonstrated that simple application of constant station travel time adjustments can improve the precision of hypocenter determinations worldwide. Through more sophisticated analyses now underway, it may be possible to realize further improvement through quantification of the coherent and azimuthally dependent parts of the station residual.

The use of theoretical seismograms is rapidly becoming a part of inversion schemes to study both earth structure and the earthquake mechanism. It is important that the accuracies and limitations of the various techniques in use be examined for different applications.

General models can be used to construct synthetic seismograms of body waves that interact with upper mantle discontinuities at different distance ranges. The variability in wave forms and the range of velocity models needed to describe them would give an indication of where regional travel time curves may be needed or of the advisability of developing average upper-mantle models regionally. In a preliminary study, it was found that in the distance range  $10^{\circ}$ – $15^{\circ}$ , wave propagation was strongly dependent on region. From  $15^{\circ}$  to  $20^{\circ}$ , only a few velocity models, differing mainly in the thickness of the low-velocity zone, were needed to satisfy the observed wave forms. For distances of  $20^{\circ}$ – $30^{\circ}$ , the wave forms were relatively stable from region to region and could be adequately described by using a radially symmetric earth model. Greater than  $30^{\circ}$ , the synthetic wave forms were transparent to upper-mantle structure. Perhaps there are two types of problem areas requiring further study. First, there are small regions of high geophysical interest, such as fault zones of descending plates. Second, there are broad scale tectonic regions that perhaps should be modeled separately; these include continental versus oceanic regions and perhaps stable versus tectonic continents.

## Earthquake Location

The locations of earthquakes in central California are systematically displaced from known fault lineations by as much as 4 km when locations are computed with a uniform velocity for the crust. When different velocity models that are appropriate to the geology are used for each side of the fault, the recomputed epicenters map on the faults. Definition of regional seismicity from locally and regionally recorded arrival time data poses special problems. Combinations of unfavorable azimuthal distribution of seismograph stations and lateral variations in velocity within a structure assumed to be homogeneous can lead to discrepancies of more than 100 km between epicenters determined by regional networks and those determined from data recorded worldwide.

Present routine hypocenter locations of global earthquakes, using teleseismic data and a spherically symmetric earth model, can be inaccurate by as much as 50 km or more in location or depth. Hence conventional global catalog earthquake locations are inadequate for defining such features as the thickness of Benioff zones, the continuity or discontinuity of subducting lithosphere slabs, and the interfaces between lithosphere plates.

Many techniques have been suggested for improving the precision of routinely determined hypocenters worldwide. One approach is to use data from a relatively few, but geographically well distributed, stations of very high sensitivity. Precise focal depths could be determined by using the master event method and S–P (transverse minus longitudinal) time intervals from nearby stations. Another approach is to process a number of closely located earthquakes jointly rather than as independent events. Programs of this type use the arrival times of seismic phases from more than one earthquake to jointly determine hypocenter locations and station adjustments to the travel time tables. Usually a calibration event (or events) whose position is independently known is used to stabilize the joint computation, but penalty functions can also be used. These methods permit more reliable (and reasonable) tectonic interpretations, identification of lineations deep within plates, and are useful in the relocation of historical earthquakes.

The Joint Hypocenter Determination (JHD) and master event method can also improve the accuracy of hypocenter location when the calibration (or master) event is accurately located by other means. In regions of complex or rapidly varying structure, however, one must resort to three-dimensional seismic ray tracing to locate earthquakes, because the station adjustments change rapidly with position. Ray tracing is a fairly complicated and expensive process. For locating earthquakes, it is necessary to find the ray which connects the hypocenter to the station. A two-point boundary value problem must be solved, and multiple paths can be a problem.

One novel approach, useful in subduction zones, is to first model *P* wave velocities in the subducting plate from thermal considerations and then use seismic ray tracing to determine slab-associated, teleseismic *P* wave residuals as functions of earthquake distance from the center of arc curvature, of station distance, and

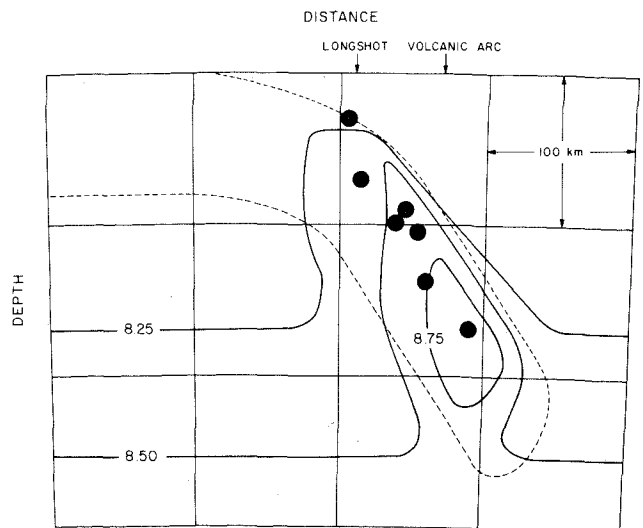


Fig. 2. Two-dimensional velocity model of a subducting slab, based on a numerical thermal model of the plate calculated for the Aleutian subduction zone. This slab model was used with seismic ray tracing to relocate the six deeper events from *P* wave arrival times at local and teleseismic stations. (From Engdahl, E. R., H. H. Sleep, H. and M-T Lin, Plate effects in north Pacific subduction zones, *Tectonophysics*, 37, 95–116, 1977.)

azimuth. These theoretically derived plate corrections, when used with a spherically symmetric earth model, can lead to considerably improved teleseismic earthquake locations.

Existing methods for determining structure in three dimensions can be modified to simultaneously determine the locations of earthquakes. This requires the least squares solution of a large but sparse system of linear algebraic equations. Methods are being sought to take advantage of this sparseness to reduce the computational burden of obtaining the solution.

A great simplification may be possible in methods for locating earthquakes in regions where the structure is specified in three dimensions. The travel times for the three-dimensional medium can be adequately estimated by integrating the slowness along paths that are only approximations to the true rays and which might, for example, be paths for a radially symmetric earth model.

Care should be used in the application of methods requiring assumptions about the crust and upper-mantle structure of the hypocentral region. In addition, any method should be carefully tested, using many events occurring in various seismic zones throughout the world, before routine application.

## Moment Tensor

The seismic moment tensor has been proposed as an effective and general representation of the seismic source that can be determined from long-period body waves or surface waves. It may be simplest to use long-period surface waves, for which calibration formulas for both amplitude and phase can be developed more reliably from observations than for body waves, because they propagate along the surface where the stations are distributed. Once the calibration formulas are established for a given station and a particular source point on the earth, a linear inversion scheme will give a quick and accurate determination of focal depth and moment tensor elements for earthquakes occurring in the vicinity of the source point.

Theoretical results have been developed for determining the multipolar expansion of a seismic source from very long period information. One can write the moment tensor retrieval as a standard linear inverse problem which does not depend on the hypocentral location. A similar scheme may be invented to recover the second term in the multipolar expansion, which does depend on the hypocentral location, from which one can determine the location of the most pointlike source.

The moment tensor is a compact general way to characterize the radiation pattern—an objective intermediate variable used to characterize the event. Moreover, the representation has the theoretical advantage of being linearly related to the observed seismograms. For small events, it is difficult to determine the focal mechanism, because small-amplitude, short-period first motions must be used. For bigger events, with good depth estimates, it is relatively easy to accurately estimate moment tensor, double-couple parameters, source-time functions, or other variables. Special studies of the extent of explosive/implosive motions at the source, and perhaps of tension components in the slip function due to the effects of asperities, would become possible. More generally, we would

benefit greatly from interpreting the moment tensor of many earthquakes in a given region in terms of focal planes. The moment tensor contains all the information ordinarily used to characterize the focal mechanism but handles this information in a more systematic and objective fashion. Knowledge of the directionality of rupture growth (for earthquakes on various plate boundaries) will be helpful toward understanding the inhomogeneities of stress within which earthquakes occur. The time dependent moment tensor (or moment rate tensor) is more naturally a part of the theory of excitation of seismic waves and can be parameterized to include a representation of the source time function. Complications could arise for large and complex events.

While there is great merit in using the seismic moment tensor to model the source, there are objections to its use on a routine basis. One objection is conservative and based on continuity with past studies. For years the dislocation model has been used with success in focal mechanism studies and has been very useful for tectonic interpretations. Its physical correspondence with the idea of a fault has been its greatest asset. Where good wave form data have been available, the dislocation model has also been shown to represent the earthquake process very accurately. Thus it would seem reasonable to continue to provide dislocation parameters for earthquakes. A second objection against using the general moment tensor formulation is based on modeling experience. In a system with errors in the data and in the model, increasing the allowed degrees of freedom will naturally improve the quality of apparent fit. An implicit assumption when doing source studies is that earth structure is known perfectly. This is never the case. Thus tradeoffs will occur through the errors between source and structure. Until these effects are better understood through further research, it may be that dislocation parameters should be used to limit the degrees of freedom. The effects of finiteness or source multiplicity may also present problems and should be topics of future research.

## Focal Mechanism

New approaches are being sought to objectively automate focal mechanism determinations. One method uses *P* wave, first-motion data from a group of earthquakes to simultaneously solve for their pressure and tension axes, with error estimates on these parameters. The statistical approach treats the first-motion data as a binary signal having noise that follows a cumulative normal distribution. Another method determines fault plane solutions from short-period amplitudes of *P* and surface reflections *pP* and *sP* and displays the range of possible solutions. Finally, linear programming has been utilized with the moment tensor formulation to find a very large volume of possible focal mechanism solutions in parameter space. While it is extremely hard to demand a double-couple solution through the use of this method, it is straightforward to place a variety of linear constraints on the system, such as finding the source which is the most isotropic, deviatoric, explosive, thrust like, etc., and it is easy to find out which data are constraining the fit. Besides *P* first motions and amplitudes, *SH* (horizontally polarized *S*) can be incorporated into the procedure. Ray tracing can also help in focal mechanism

studies. First-motion data from earthquakes in complex regions often appear to be inconsistent with double-couple mechanisms; the first-motion data does become consistent, however, when ray tracing with known near-source velocity structure is used to map stations onto the focal sphere.

## Synthetic Seismograms

There have been great advances in modeling both long-period seismograms for the far field and strong motion records for the near field. Unfortunately, data of the latter are extremely sparse; one of the next goals in seismology should be to extract strong motion information from the more abundant teleseismic data. The problem of computing synthetics that incorporate the behavior of a fault for short distances (i.e., a few degrees) away from a fault appears tractable. In principle, the azimuthal behavior of the wave forms ought to provide information on how a fault ruptures, the stress drop, frictional behavior, and so on. The biggest difficulty probably will be in distinguishing what part of the observed data results from fault mechanisms, local structure, attenuation, or scattering.

Various approaches have been attempted to invert body waves for source mechanisms. These are characterized by different source representations, different measures of the synthetic fit to data, and different kinds of data. A nonlinear search of a complicated parameter space (mechanism, time history, and source depth) seems to provide constraints on source mechanisms by using only tiny data sets. However, there seems to be a high degree of dependence not only on source depth but also on velocity structure in the source region.

The determination of source parameters of small earthquakes is nontrivial because of the lack of good quality short-period *P* wave first motions. In one routine method, source parameters for earthquakes with  $4 < m_b < 5$  are determined by a complete analysis of all data, including short-period *P* wave motions, long-period Rayleigh- and Love-wave amplitude and phase spectra, and short-period *Lg* (a guided wave in the continental crust) spectra. Success depends upon a redundant data set. The data reduction steps are (1) digitization, (2) spectral analysis, (3) multiple-filter analysis, (4) sieving spectral amplitudes through a group velocity window, (5) checking for inconsistencies in the data set, noting the  $180^\circ$  symmetry of surface wave amplitude radiation patterns for double-couple sources, (6) searching through the strike, dip, slip, and focal depth parameter space for the best fit between observed and theoretical radiation patterns, and (7) choosing the final solution, from the set of possible surface wave amplitude solutions, which satisfies the limited surface wave phase data and *P* wave first-motion data. *Lg* spectra are processed separately to obtain corner frequency estimates. The final result is a tabulation of strike, dip, slip, depth, seismic moment, and corner frequency.

Source inversions, from the point of view of a stress relaxation model, closely parallel normal mode techniques as the Green's functions are expanded in eigenfunctions of the earth model. Ultimately, the fit is performed in the frequency domain, and information on orientation and the growth of the stress-relaxation surface can be extracted.

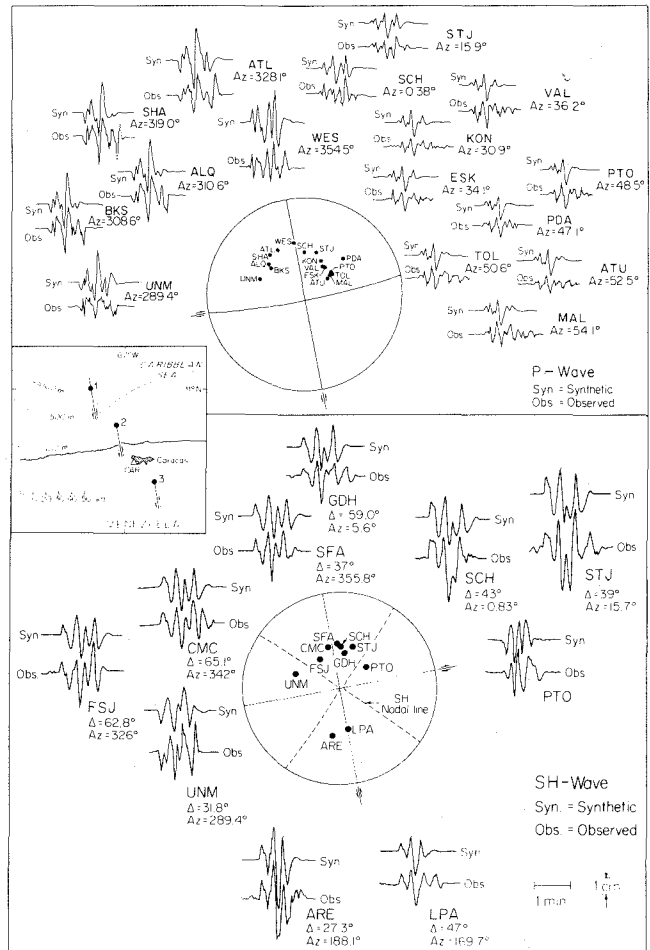


Fig. 3. Comparison of synthetic seismograms that are generated by using generalized ray theory to observed *P* and *SH* wave seismograms at WWSSN stations around the epicenter. The faulting process is modeled by three different sources separated in space and time and occurring in succession from northwest to southeast on three seemingly en echelon left lateral strike slip faults. (From Rial, J. A., The Caracas, Venezuela, earthquake of July 1967: A multiple-source event, *J. Geophys. Res.*, 83, 5405-5414, 1978.)

## Magnitudes

Although seismic moment probably best expresses the overall size of earthquakes there is a need to calculate magnitudes more reliably and meaningfully. The body wave and surface wave magnitudes  $m_b$  and  $M_s$  are still very important in many applications, such as in discriminating nuclear explosions from earthquakes, and more effort should go into calibrating regions for  $m_b$  and  $M_s$  values that are consistent from region to region.

Related work involves picking seismic phases automatically from short-period data. A seismogram is passed through a band of narrow bandpass filters and, in each case, the maximum in the envelope of the filtered trace picked out. Phases are then isolated by looking for coincidences in time of high-amplitude envelope points (i.e., a non-dispersive arrival). The method seems to be very successful at identifying phases in noisy data (or in the coda) and in defining a characteristic behavior when two phases are interfering. Since phase amplitudes are preserved as a func-

tion of time, this technique provides a means of representing short- or long-period source complexities and may help to sort out multiple events. It can also provide estimates of magnitude at precise frequencies and specific times on the seismogram. For this latter task, the envelope function should be characterized with the least number of parameters and then calibration methods developed for each band, such as Gutenberg and Richter did for their magnitudes. The calibration formulas for the spectral envelopes can be developed empirically by a systematic study of their dependence on focal depth, epicentral distance, earthquake magnitude, and other known parameters of the path and source effects.

Although  $m_b$  as defined is useful for certain applications (discrimination, etc.), it is not adequate to represent the content of high-frequency energy for distant earthquakes. The 1-Hz energy peak shifts to later arrivals, and the duration of the short-period signal increases as the size of the earthquake increases. Because the complexity of 1-Hz signals for earthquakes of a given size varies greatly, the signal needs to be integrated over longer time windows than the first three cycles to adequately represent the high-frequency content of distant earthquakes.

## Seismic Moment

The double-couple seismic moment should be routinely reported, because it is the most useful single parameter measure of source size. Double-couple seismic moments can be estimated from amplitude spectra of long-period surface waves and free oscillations. Attempts have been made to relate seismic moment to very long period dispersed-Rayleigh waves using normal mode theory. This method does not require accurate information on phase velocities. The idea was to limit measurements to quantities which can be unambiguously measured experimentally. To a first approximation the average amplitude of each normal mode will yield stable estimates of earthquake moment  $M_0$  without having to laboriously determine the fault plane orientation for the earthquake or the mantle wave spectral densities from conventional seismograms. Body waves may also be used, but there are some uncertainties about their scattering and attenuation corrections.

A broad new magnitude scale ( $M_w$ ) has been defined that relates directly to seismic moment:

$$M_w = 2/3 \log M_0 - 10.7$$

$M_w$  is a more physically relevant parameter for estimating the size of great earthquakes and generally agrees with  $M_s$  between  $5 \leq M_s \leq 7$  and with  $M_L$  between  $3 \leq M_L \leq 7$ . The new magnitude scale assumes (1) constant stress drop for all earthquakes, and (2) a relation to the total seismic wave energy. In the future it will be possible to routinely take advantage of the greater generality of  $M_w$ ; the primary advantages include the fact that  $M_w$  is a unified scale valid at all attainable earthquake sizes and, because  $M_w$  relates directly to moment, it may be possible to measure it more precisely in the future.

## Parameterization

The means of parameterizing events to satisfy a broad class of users must be developed. The

parameters could be the most general and routinely measurable quantities on the seismogram that are determinable by automatic or semiautomatic means. The ultimate goal would be to characterize the source in terms of such physical parameters as stress drop, rupture rate, fault length, depth, and variability of stress drop. A simpler goal, however, might be to identify all impulsive earthquakes because of their usefulness in determining source functions. Because parameters often have different definitions to different people (e.g. complexity), it has been suggested that several minutes of rotated short- and long-period wave forms at the beginning of large events be routinely published and that the reporting threshold be lowered according to demand and resources.

## Catalogs

Earthquake parameter catalogs serve the needs of two, often disconnected, user groups. The first are those who use the catalog as a source of information by itself. This group includes the public, the news media, and researchers in areas such as seismic risk analysis, regional seismotectonics, analysis of seismic gaps, and discrimination. The second are those who use the catalogs as an index so that a particular subset of events can be selected for special study and detailed analyses (e.g., wave form study).

The first group requires a complete catalog, or as complete as possible, and accurate parameters. This group is generally interested in small events as well as large events, which suggests that efforts should be made to lower the threshold for reporting parameters. These users tend to have little appreciation for the accuracy (or lack thereof) of many of the quoted parameters and often use the reported parameters as if they had no uncertainty associated with them. Routine use of only a limited number or highly weighted set of high-quality stations is one way to achieve more uniform error bounds on earthquake parameters. The inclusion of more realistic error bounds will help a little; the real problem, however, is to remove systematic bias (e.g., from short-period stations with strong patterns of azimuthal anomalies), and this is not an easy task. It is essential that more effort be directed to determining better calibration parameters for the earth. One view is that seismologists are too quick to go from uncalibrated parameters to physical interpretations. It has been suggested, for example, that mere measurement of moment, without knowledge of crustal characteristics, could lead to estimates of fault lengths and displacements for eastern U.S. earthquakes that would be in error by an order of magnitude or more.

The second group of users is much easier to satisfy. Researchers using the catalog as an index are usually not as interested in accurate locations or depths or magnitudes as the first group, because they will often insist on recomputing these quantities themselves. These users tend to be much more interested in large events with much data, such as provided by the World Data Centers, where special interest events are particularly well documented. Essential features such as focal mechanism, aftershock distribution, and reproductions of seismograms for the main shock and significant aftershocks should be made available. Information on the availability and quality of data would be very useful in the catalogs.

It is interesting to consider the moment tensor question in the light of these two groups. As things stand today, if the moment tensor were routinely published, most of the second group probably would not believe it, preferring to compute it themselves using their own methods. On the other hand, the first group would tend to accept the numbers that are published without being aware of their uncertainty. Problems can arise when an event occurs for which the computed moment tensor has a substantial isotropic component. A member of the first group might identify the event as an explosion, when the isotropic component of the moment tensor may actually be a spurious effect of propagation.

## Other Considerations

The basic problem that remains may be calibration; the idea of choosing a subset of good, well-operated stations and using this subset in the estimation of parameters is strongly supported. The inclusion of station travel time and amplitude corrections and regionalized travel time tables and amplitude-distance curves could do much toward the elimination of systematic bias. This may require monitoring of interesting regions with temporary local networks to build a set of calibration events. A major task of reporting agencies may be the selection of the primary network and the determination and implementation of regionalized corrections.

There is some merit in preserving continuity with historical catalog data. Use of a new standard earth model without the use of the associated station corrections may be pointless. If, however, a new travel time standard is introduced for routine locations, then it will be important that previous locations should be relocated and a new catalog compiled, otherwise there may be problems of interpretation for years ahead. Continuity is important with respect to locations and magnitudes; many people, who will not be aware of subtle changes, use them. If changes are made, previous data should be reworked and published. Prominent announcements are needed whenever changes are made in the derivation of reported earthquake parameters. It would be useful to keep and update a catalog of seismic moments and focal mechanisms as they appear in the literature.

Resources are the limiting factors in routine reporting of earthquake parameters on a global basis. Research should be directed toward making more of the sophisticated analysis routine. Analysts with considerable experience will have to be involved on a long-term basis and changes may be possible only through increased automation.®

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